Assessment of large-scale wind resource features in Algeria

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ABSTRACT

This study presents an assessment of the wind potential over the whole Algerian territory, based for the first time on a reanalysis dataset. Thereby, 33 years (1981–2014) of 6-hourly wind components from ERA-Interim reanalysis are used for assessing the wind energy large-scale features over the largest country in Africa. The ERA-Interim data are validated against observational wind speeds from 42 sites across Algeria by using the two-sample Kolmogorov-Smirnov and the Wilcoxon–Mann–Whitney tests, while the Generalized Extreme Value (GEV) theoretical distribution is used to characterize wind speeds. Overall, the ERA-Interim dataset validation reveals good agreement with observations in the south and less near the coastline. The mean wind speed and prevailing wind direction are assessed on the annual, monthly and hourly timescales. Mean wind speeds ranging between 2.3 m s^{-1} in the North, and 5.3 m s^{-1} in the South are found. Furthermore, the windiest periods are the warmer months and during daytime over almost all of the country. The gridded wind energy outputs for a representative wind turbine (850 kW) are also assessed. These informations are of foremost relevance to decision-makers and to the energy production sector in Algeria, providing guidelines for new wind farms installations.

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1. Introduction

Since 2011, Algeria has made the promotion of renewable energies one of its main challenges for meeting the growing energy demands and to replace gradually the use of fossil fuels, which are currently the main resource for the national electric power generation [1,2]. For this purpose, an ambitious strategy for encouraging and developing renewable energy production is being implemented, where the wind energy constitutes the second axis of development, with an electricity production expected to reach about 5 GW in 2030 [3]. However, for an efficient exploitation, it is critical to have accurate information on the potential wind resource at a given place before the installation of wind energy generators/turbines. Thus, wind energy is regarded as one of the most important line of research within different scientific institutions in Algeria, where several studies on wind resource assessment have been carried out since 2000, especially during the last ten years, at different regions over Algeria.

Aiming at establishing wind maps in Algeria, some studies were

conducted using data collected from meteorological masts at different temporal resolutions. In 2000, Merzouk [4] produced a wind atlas at the 10 m level, for which wind data taken every 3 h from 48 weather stations were used, covering almost all the topographic zones of the country. In 2011, Chellali et al. [5] updated the wind map of Algeria by performing a spectral analysis to study wind cycles, using daily mean wind speed collected by a network of 37 meteorological stations. Still using daily mean wind speed, the assessment of the Algerian wind resource was made by Boudia et al. [6], with data recorded over the last decade from 63 meteorological stations distributed all across the Algerian territory, plus 24 in neighboring countries close boundaries, so as to refine the tracing of the borders map. The latest study mapping the wind speed in Algeria was carried out in 2018 by Nedjari et al. [7], where hourly and 3-hourly data, mostly recorded between 2004 and 2014 from >70 new sites, were used to update the previous wind resource assessment. The wind potential in different Algerian regions has been revised by incorporating new weather stations, such as Mechria [6], Hassi R'mel [5] and In Salah [7], to cite only the most windy sites. Nevertheless, the data quality and spatial coverage of the Algerian Meteorological Office (ONM) network, with meteorological stations predominantly located in airports and primarily devoted to the aerospace market, clearly limits an accurate wind

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resource assessment throughout the country.

Therefore, alternative data sources must be explored to quantify the actual wind resources, by providing accurate estimates of the available wind power in Algeria, where there is a lack of high-quality *in situ* datasets available over long time periods. For this purpose, reanalysis data, which commonly represent an assimilated form of land based meteorological stations, buoy, ship and satellite data [8,9], with gridded wind data covering the whole target area over relatively long and uninterrupted time periods, is expected to provide a more accurate and spatially coherent representation of the large-scale wind resources, particularly in regions where no wind data measurements are available. This approach is particularly useful in such a large country as Algeria, with an area of almost 2.3 million km². In fact, in Algeria, *in situ* surface data provided by meteorological measuring masts are generally concentrated in the north, along the coastline and in the highlands, while they are very sparse in the south, especially over the Sahara region, which indeed represents the largest part of the country. Furthermore, reanalysis data have been used to study wind resources in different regions in Europe, such as Northern Ireland [10], Great Britain [11], Germany [12] and Iberia [13,14], in addition to several offshore studies worldwide [15–17]. The reanalysis data can thereby be a good alternative to the more conventional wind speed analysis, based solely on weather station data.

A review of the literature demonstrates that a number of studies have been carried out using wind data provided by the ERA-Interim reanalysis dataset (European Centre for Medium-Range Weather Forecasts Re-Analysis Interim) [18], in different areas of the world. As an illustration, Mattar et al. [19] assessed the offshore wind power potential for the central coast of Chile. Nagababu et al. [20] evaluated the wind potential in six locations in India. Carvalho et al. [21] simulated the offshore wind energy resource over the Iberian Peninsula. Onea et al. [22] assessed the wind resource in the nearshore of the Mediterranean Sea. Overall, as also reported by Mattar et al. [23], the values delivered by ERA-Interim are a valid source of data for analyzing wind speed and direction, as well as offshore wind power, mostly in regions with low density weather

station networks.

In the present study, the wind potential over the whole Algerian territory is assessed, using for the first time a reanalysis dataset (ERA-Interim), with 6-hourly wind data at the 10 m level and over the period of 1981–2014 (33 years). The first part of the study is devoted to the validation of the reanalysis wind data with *in situ* measurements. The second part of the study provides an assessment of the wind resource using the ERA-Interim dataset. The mapping of the diurnal variability in wind speed and prevailing wind direction over Algeria is also innovative. Lastly, the performance of a selected wind turbine of 850 kW rated capacity, specifically designed for electric power generation, is examined over the whole Algerian territory.

2. Data and methods

2.1. Reanalysis data

The ERA-Interim reanalysis database, generated by the European Centre for Medium-Range Weather Forecasts (ECMWF), is produced with a sequential data assimilation system [18,23], available from 1979 onwards [24]. This database counts 60 vertical levels, is provided on a regular grid with spatial resolution of 0.75° latitude × 0.75° longitude (roughly 70–80 km) and with a time resolution of 6 h [25]. In the present study, the 10 m zonal and meridional wind components (u, v) at 00, 06, 12 and 18 UTC (4-hourly data) are retrieved. The period covers 33 years of data, from 1 January 1981 to 31 December 2014, and over a geographical sector that covers the whole Algerian territory: 18–38°N, 9.5°W–13°E.

2.2. Wind reanalysis

In order to estimate the Algerian wind energy potential, the methodology shown in Fig. 1 is adopted. The zonal and meridional wind vector components (u, v) at a height of 10 m above ground level (a.g.l.) were retrieved from ERA-Interim [26] and were used to

Fig. 1. Fluxogram of the methodology used to estimate the wind energy potential.

compute both the wind speed V and the wind direction D for each gridpoint by using the following equations [27,28]:

$$V = \sqrt{u^2 + v^2} \quad (1)$$

$$D = \text{tg}^{-1}(u, v) \frac{180}{\pi} + 180 \quad (2)$$

2.3. Vertical extrapolation of wind speed data

As ERA-Interim wind speed data are given at 10 m a.g.l. and knowing that near-ground wind speed changes rapidly with height, the reanalyzed wind speed must be extrapolated to the wind turbine hub height in order to more realistically evaluate the wind energy production potential. In this study, the power law given by the following equation is applied [29,30]:

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1} \right)^\alpha \quad (3)$$

where V_2 is the extrapolated wind speed at height h_2 , V_1 is the available wind speed at height $h_1 = 10$ m and α is the ground surface friction coefficient. Given that almost all of the study area is onshore, the 1/7 power law [31] is adopted herein. In effect, this is the default value when no wind shear coefficient measurements are available at a given site [32].

2.4. Wind energy outputs

For wind energy output calculations, the characteristics of the Gamesa G52 wind turbine with a rated capacity of 850 kW are used, knowing that this is the only turbine model installed in Algeria, at the single wind park connected to the network in Adrar, in the south of the country. In this study, we used the nominal power curve given by the manufacturer to estimate the power output at each time step (with 6-h intervals). The characteristics of the selected wind turbine are summarized in Table 1 and the corresponding power curve is displayed in Fig. 2. The Gamesa G52 wind turbine characteristics used herein are provided by SKTM (Shariket Kahraba wa Taket Moutadjadida) company through an SKTM-CDER convention.

To estimate the energy output, the following method described in Ref. [33] was applied. First the power curve given by the manufacturer was directly used to estimate the power output (P_i) at each time step ($i = 1, 2, \dots, n$). Then the gross mean power output (P) over the whole studied sector is estimated by $\left(P = \frac{\sum P_i}{n} \right)$. Finally, the gross energy output (E) for a period of time (t) is calculated as ($E = Pt$).

Table 1
Gamesa G52 wind turbine parameters.

Model	Gamesa G52
Rated power (kW)	850
Rotor diameter (m)	52
Hub height (m)	55
Swept area of rotor (m ²)	2122
Cut-in-wind speed (m s ⁻¹)	4
Rated wind speed (m s ⁻¹)	15
Cut-out-wind speed (m s ⁻¹)	28

Fig. 2. Power curve in kW of the Gamesa G52 wind turbine.

2.5. Observational data

For the validation of the reanalysis wind fields, *in situ* daily mean wind speed, also at 10 m a.g.l., collected by a network of 42 weather stations across Algeria, were used. Nevertheless, due to the relatively low density of meteorological stations over Algeria and to the lack of regular wind speed measurements, with frequent data gaps, ERA-Interim data were validated for a single year period (2014), when data availability was maximum over all stations. Given the effect of the orography on wind speed [34], and since Algeria comprises several geographical areas, with different reliefs and climates, from the northern Mediterranean coastline to the Sahara in its southernmost area, going through the Tell and the Highlands (in the Atlas Mountain Range), the number of sites in each geographical zone is provided in Table 2. The geographical coordinates of the *in situ* meteorological stations and of the closest ERA-Interim gridded boxes are given in Table 3.

2.6. Validation

A comparison between ERA-Interim reanalysis and weather station measurements of daily mean wind speed, which are both at 10 m a.g.l., is herein carried out for 2014. The validation of the ERA-Interim data was performed as follows. First, due to the fact that the 42 weather station records are of daily mean wind speed, the daily means of ERA-Interim wind speed at the nearest gridpoint were calculated. Furthermore, although the two-parameter Weibull function is conventionally used in wind energy assessments at different regions around the globe [35–37], the Generalized Extreme Value (GEV) distribution was herein chosen for this purpose, as it indeed corresponds to a generalization of the Weibull distribution, allowing more accurate representations of the empirical distributions [38,39]. The three-parameter GEV probability density function is defined as follows [40,41]:

Table 2
Number of sites in each geographical area.

Site classification	Number of sites
Littoral	6
Tell	10
Highlands	12
Sahara	14

Table 3
Geographical coordinates of 42 *in situ* wind measurement sites over Algeria, with data collected in 2014, and the closest ERA-Interim gridpoints.

Nb	Station	Measurement site			ERA-Interim gridpoint		
		Lon (°)	Lat (°)	Elev (m)	Lon (°)	Lat (°)	Elev (m)
1	Adrar	−0.28	27.88	263	0.00	27.75	297
2	Ain-Safra	−0.60	32.76	1059	−0.75	33.00	1296
3	Annaba	7.81	36.83	4	7.50	36.75	15
4	Batna	6.18	35.75	1052	6.00	36.00	1005
5	Bechar	−2.23	31.50	773	−2.25	31.50	775
6	Bejaia	5.06	36.71	2	5.25	36.75	0
7	Biskra	5.73	34.80	87	6.00	34.50	−7
8	Borj Bou Arreridj	4.76	36.06	930	4.50	36.00	1366
9	Bou-Saada	4.20	35.33	461	4.50	35.25	570
10	Chlef	1.33	36.21	143	1.50	36.00	776
11	Constantine	6.61	36.28	694	6.75	36.00	1014
12	Dar-El-Beida	3.25	36.68	25	3.00	36.75	225
13	Djanet	9.46	24.26	1054	9.75	24.00	982
14	El-Bayadh	1.00	33.66	1347	0.75	33.75	1276
15	El-Kheiter	0.06	34.15	1001	0.00	34.50	1096
16	Ghardaia	3.81	32.40	450	3.75	32.25	460
17	Ghazaouet	−1.86	35.10	5	−1.50	35.25	237
18	Illizi	8.41	26.50	558	8.25	26.25	781
19	In-Amenas	9.63	28.05	562	9.75	27.75	534
20	In-Salah-North	2.51	27.25	269	3.00	27.00	357
21	Jijel-Achouat	5.78	36.80	2	6.00	36.75	538
22	Kasr-Chellala	2.31	35.16	801	2.25	35.25	804
23	Laghouat	2.93	33.76	765	3.00	33.75	746
24	Mascara-Ghriss	0.15	35.21	513	0.00	35.25	620
25	Mechria	−0.43	33.58	1149	−0.75	33.75	1079
26	Milliana	2.23	36.30	721	2.25	36.00	556
27	Mostaganem	0.11	35.88	138	0.00	36.00	0
28	Msila	4.50	35.66	442	4.50	36.00	1365
29	Naama	−0.30	33.26	1166	0.00	33.00	1094
30	Oran Es Senia	−0.60	35.63	90	−0.75	36.00	0
31	Ourgla	5.40	31.93	141	5.25	32.25	163
32	Relizane	0.55	35.73	75	0.75	36.00	44
33	Saïda	0.15	34.86	752	0.00	34.50	1096
34	Setif	5.41	36.18	1038	5.25	36.00	901
35	Sidi-Belabes	−0.61	35.20	476	−0.75	35.25	563
36	Tamanrasset/Aguenna	5.46	22.80	1377	5.25	22.50	1065
37	Tebessa	8.13	35.41	813	8.25	35.25	1102
38	Tiaret	1.43	35.35	1127	1.50	35.25	1018
39	Timimoun	0.28	29.25	312	0.00	29.25	346
40	Tindouf	−8.13	27.70	431	−8.25	27.75	459
41	Tlemcen-Zenata	−1.46	35.01	247	−1.50	35.25	237
42	Tougourt	6.13	33.11	85	6.00	33.00	78

$$f(v)=\frac{1}{\alpha}\exp\left\{-\left[1+k\frac{(v-\mu)}{\alpha}\right]^{-\frac{1}{k}}\right\}\left[1+k\frac{(v-\mu)}{\alpha}\right]^{-1-\frac{1}{k}}\tag{4}$$

for $k(v-\mu)/\alpha>-1$, where $f(v)$ is the probability of observing a given wind speed, v , μ is the location parameter, α is the scale parameter and k is the shape parameter. The average wind speed v_m can be calculated on the basis of the GEV parameters, as given below [38]:

$$v_m=\mu+\frac{\alpha}{k}[1-\Gamma(1+k)]\tag{5}$$

For a good results reading, two metrics defined in Ref. [42] were selected to assess the accuracy of the reanalysis dataset, i.e. the mean absolute error (MAE) and mean absolute percentage error (MAPE). The absolute value was added to the mean percentage error to evaluate only the difference, without considering the wind potential overestimation or underestimation.

In order to assess whether the observed and the ERA-Interim data have the same empirical distributions (sample withdrawn from the same population), the two-sample Kolmogorov-Smirnov (KS) test [43] is applied, at 5% significance level. In the KS test, the

null hypothesis states that the two samples belong to the same population, against the alternative hypothesis that they are from different populations [44,45]. The KS test is modified to determine if the two distributions have the same shape only, without taking into consideration their medians. The Wilcoxon–Mann–Whitney (WMW) test [43] is applied to compare the medians at 5% significance level. The WMW null hypothesis considers that the two samples belong to populations with equal medians [44,46].

3. Results and discussion

3.1. Validation of ERA-Interim wind data

Fig. 3 illustrates the spatial distribution of the annual mean 10 m wind speed for 2014, estimated using the GEV distribution, for the observed data (circles) and for the ERA-Interim reanalysis (shading). A higher homogeneity in the wind speed values at the sites located in the south of the country is observed. Figs. 4 and 5 display the errors in the wind speed of ERA-Interim data compared to observed wind speeds, showing MAE (m s^{−1}) and MAPE (%) by site classifications. Fig. 4 shows that the results mirrored those observed in the spatial distribution given in Fig. 3 for the Sahara sites, where MAE and MAPE have lower values in

Fig. 3. Spatial distribution of 42 measurement points, along with annual mean wind speed for 2014 (circles) and over the 10 m wind map from ERA-Interim (shading in m s^{-1}).

Fig. 4. Error in wind speed of ERA-Interim data in each of the four site classifications regarding Algerian topography, compared to *in situ* measured wind speeds.

the more northern sites, i.e. 0.47 m s^{-1} and 12.71%, respectively. However, at Tellian sites in the north, the results are not so different from those of the Sahara sites in terms of MAE, while the MAPE is about 8% higher. The results for the highland sites show MAE equal to 0.76 m s^{-1} and MAPE near 21%. The Algerian coastal sites reveal the worst results, with the highest MAE and MAPE, equal to 1.5 m s^{-1} and 61.18%, respectively.

The results for each site reveal that Batna, in Algerian Highlands, presents the highest agreement between observed and reanalyzed wind speed (Fig. 5). Fig. 4 also highlights that the worst results are found in the coastal sites, where the highest value of MAE is equal to 2.19 m s^{-1} at Oran Es Senia site, while the highest value of MAPE is found in Ghazaouet (107%). In addition, among the 42 analyzed sites and taking into consideration the MAPE evolution, it is worth noting that there are 20 sites where the error is $<15\%$, of which 12 sites are from the Sahara, 5 from North-Tellian, 3 from the highlands and none from the coastline. This can be partly explained by the deviations between weather stations and the ERA-Interim nearest gridpoint, where the gridpoints corresponding to 4 out of 7 sites in the north coast fall offshore, on the Mediterranean sea.

These sites are Ghazaouet, Mostaganem, Oran Es Senia and Bejaia, of which the MAPE results are the worst ($>50\%$) among the 42 analyzed sites.

In order to better understand the behavior of wind speed in Algeria, Fig. 6 shows the time series weather data during the year 2014, for a representative region of each site classification regarding Algerian topography. It is worth noticing that in the three northern geographical areas in Algeria (Lottoral, Tell and Highlands) the wind remains relatively calm during the warm months (from June to October), whereas the wind speed tends to increase for the rest of the year. However, for the Algerian Sahara (Fig. 6-d), it is seen that the wind is relatively important throughout the year, with a maximum reached in the period from February to March.

Fig. 7 depicts the wind deviation errors as a function of the elevation difference between weather stations and the nearest gridpoint from ERA-Interim. Higher errors in both MAE and MAPE tend to be related to higher elevation differences. Thus, it is important to emphasize that mountainous areas and strong local winds are not entirely resolved by ERA-Interim, which is due to its coarse spatial resolution of 0.75° latitude $\times$ 0.75° longitude ($\sim 70\text{--}80 \text{ km}$ grid spacing). Hence, the present assessments are essentially focused on large-scale features. In order to accurately downscale this information, mesoscale models should be coupled with reanalysis and should also be complemented by the installation of local wind sensors, an approach that is out of the scope of the present study.

The GEV distributions at 10 m for the different weather stations and the corresponding nearest gridpoint from ERA-Interim and for 2014 are divided by tests result and plotted in Figs. 8–11. The respective boxplots and the KS and WMW test results are also shown. Fig. 8 depicts the sites where the two tests were validated. Fig. 9 gives results for sites where only the KS test was validated. Fig. 10 shows the results for the site where only the WMW test provided validation, while Fig. 11 gives the rest of the sites, where both tests were rejected. Fig. 8 shows only two sites where the two datasets are drawn from the same distribution and with an equal median. From Fig. 9, it is observed that at 9 sites among the 42 analyzed, the *in situ* measurement and ERA-Interim datasets are drawn from the same distribution, but have different medians. Conversely, from Fig. 10, it is observed that 11 sites with equal medians, but not having similar distributions. Regarding Fig. 11 and 20 sites present different distributions and medians. The results from KS and WMW tests are summarized in Fig. 12.

In agreement with the previous results regarding MAE and MAPE, Fig. 12 shows that among the 7 sites located on the coast, the two tests were rejected at 5 sites, though 4 of them correspond to ERA-Interim griboxes falling on the Mediterranean Sea. Furthermore, from the 15 sites located in the Sahara (southern Algeria), there are only 4 sites where both tests are rejected. The rest of the Sahara sites have databases that have either the same distribution or an equal median, except for the site of In-Amenas, in the extreme southeast, where the two tests showed agreement between data. The second site where both tests were validated is Mascra-Ghriss, located in northern Tell. This part of Algeria includes 4 sites among 9 where the two tests were rejected, while an almost identical ratio is found in the Highlands, with 5 sites from 11, where both KS and WMW tests were rejected. Therefore, for 2014, more than one half of the analyzed sites either present the same distribution or equal medians. Hence, a reasonable agreement between ERA-Interim wind data and observations is found, but it should be bear in mind that the ERA-Interim reanalysis only capture large-scale features of the wind patterns, not properly resolving local winds, which may be particularly relevant in mountainous and coastal areas. This gap between large-scale wind and local winds, measured by weather stations, should be taken into account when

Fig. 5. Error in wind speed of ERA-Interim data by site classifications (a) North-Coastal, (b) North-Tellian, (c) Highlands, (d) Sahara, compared to *in situ* measured wind speeds.

interpreting the discrepancies found between reanalyzed and observed winds.

3.2. Wind resource maps

Wind speed and prevailing wind direction from ERA-Interim, at 10 m and for the period 1981–2014 over Algeria are shown in Fig. 13. Although wind speeds are, as expected, greater over the sea than over land, the wind map shows that the mean wind speed in Algeria exceeds 5 m s^{-1} in the south, on the most windy area limited as follows: 26° – 29°N , 1° W– 5°E . Moreover, the Algerian Sahara is windier than the northern part of the country. It is still worth noting that the prevailing winds in Algeria are mostly easterlies over the Sahara and westerlies over northern Algeria.

The maximum mean wind speed equals to 5.3 m s^{-1} , with a predominantly East-North-Easterly wind located at the site of In Salah, with the following coordinates: 27.26°N and 2.73°E . Despite the lower average wind speed, these results are in accordance with the last updated wind map, established in 2018 [7], which no longer shows the Adrar region as the windiest region in Algeria, as seen in the previous Algerian wind atlases [4–6,47]. On the other hand, it is shown that the minimum mean wind speed, with a value of 2.3 m s^{-1} and predominantly blowing from the northwest, is located in the Batna region, in the Eastern part of Algerian Highlands, with the following geographic coordinates: 35.41°N and 6.02°E . However, according to the last update of the Algerian Wind Atlas [7], it is the site of Maghnia in the extreme northwest, with the Moroccan boundary and open to the Mediterranean sea, which represents the least windy region, with an annual mean wind speed of less than 3 m s^{-1} . Although the south of the country is windier

than the north, southeastern Algeria, near the Ahaggar region (24.44°N and 5.91°E), remains relatively less windy, with an average wind speed of 3.3 m s^{-1} , when compared to the rest of the Sahara region, where the mean wind speed exceeds 4 m s^{-1} .

To estimate the wind resource in any region for energy production, it is important to quantify not only the average energy resource, but also the expected variability at different levels by establishing different assessments, such as an analysis of the diurnal and monthly timescales. Fig. 14 gives the monthly maps of the wind resource over Algeria. The period between March and August is clearly the windiest over most of southern Algeria, while the period between February and April is the windiest in the north. On the other hand, the less windy period in the south is from October to December, while in the north it extends over a longer period, from June to October. This is generally consistent with the latest study on monthly variability [6], where it was found that the period from March to June is the windiest throughout the country, while the autumnal months are the least windy. Regarding the prevailing wind direction, in northern Algeria winds are predominantly westerly from October to April, while during the period from May to September easterly winds occur over the Highlands. Additionally, over the windiest area in Algeria, near In Salah, winds are predominantly east-north-easterly throughout the year, where the maximum mean wind speed reaches 6 m s^{-1} in July. Nonetheless, in the latest study on monthly variability [6], the highest monthly mean wind speed is assessed in May, with 8.2 m s^{-1} at Hassi R'mel region, 600 km further north.

In order to provide additional information on the wind conditions over Algeria, the hourly evolution of the mean wind speed is presented in Fig. 15. Important diurnal changes are apparent,

Fig. 6. Time series weather data for a representative weather station of each region during 2014.

Fig. 7. Wind errors (a) MAE and (b) MAPE, as a function of the elevation difference between weather stations and the nearest gridpoint from ERA-Interim.

particularly in southeastern Algeria at 06 and 12 UTC (Coordinated Universal Time). The minimum value was recorded at 06 UTC (1.9 m s^{-1}) in the northeast (35.57°N and 5.76°E), while the maximum value is obtained at 12 UTC (5.8 m s^{-1}) still at the windiest area of Algeria, located in the south, near In Salah, where wind rarely blows from the north or even from the west, but is

predominantly from northeast at 00, 06 and 18 UTC and from east at 12 UTC. Overall, Algeria is windy as a whole at 12 UTC, while relatively weak winds prevail at nighttime.

In terms of wind direction, nearly the same pattern is found, i.e. mainly easterlies in the south and westerlies in the north at 00, 06 and 12 UTC. However, different results can be found at 18 UTC,

Fig. 8. GEV distributions and boxplots of the daily mean wind speed data recorded in 2014 for measured and ERA-Interim data. The outcomes of the KS and WMW tests are also shown, with no * indicating the validation of both tests.

Fig. 9. GEV distributions and boxplots of the daily mean wind speed data recorded in 2014 for measured and ERA-Interim data. The outcomes of the KS and WMW tests are also shown, with an * indicating a rejection of the null hypothesis for the WMW test.

where northerly and southerly winds appear simultaneously in northeastern Algeria, whilst northerly and westerly winds arise

over the rest of northern Algeria. With respect to southern Algeria, at 18 UTC, even though winds are predominantly from northeast

Fig. 10. GEV distributions and boxplots of the daily mean wind speed data recorded in 2014 for measured and ERA-Interim data. The outcomes of the KS and WMW tests are also shown, with an * indicating a rejection of the null hypothesis for the KS test.

Fig. 11. GEV distributions and boxplots of the daily mean wind speed data recorded in 2014 for measured and ERA-Interim data. The outcomes of the KS and WMW tests are also shown, with an * indicating a rejection of the null hypothesis for both tests.

Fig. 11. (continued).

over most of the Algerian Sahara, a clear shift in wind direction over southeastern Algeria can be found, where wind blows simultaneously from the east, west and north.

3.3. Wind energy map

By taking into account the wind speed calculated during the 33-year wind reanalysis at 10 m over the whole study sector (28 latitudes $\times$ 32 longitudes = 896 gridpoints) and the characteristics of the Gamesa wind turbine, the wind energy output on a daily basis has been computed and plotted in Fig. 16 for a hub height at 55 m. In line with the previous results, the site of In Salah, southern Algeria, is the region with the highest daily wind energy potentially generated by the selected wind turbine, reaching 6 MWh day^{-1} . Further, most of the Algerian Sahara shows quite acceptable results for wind energy production, around 4 MWh day^{-1} , except over the southeasternmost region, where the potential is often less than

2 MWh day^{-1} , with a minimum value of only $1.65 \text{ MWh day}^{-1}$ assessed at the geographical coordinates: 24.55°N and 5.57°E .

Regarding northern Algeria, northwards of the 33°N parallel, the results suggest a minimum production of about $0.36 \text{ MWh day}^{-1}$ in the northwest, near the borders with Morocco, at the site of Tlemcen (34.94°N , 1.30°W). Furthermore, for most of the Mediterranean coastline, particularly in the west, the daily energy production can reach a maximum of 4 MWh , while in the western part of the Highlands the maximum is of about 3.2 MWh day^{-1} , near the site of Mechria (33.53°N , 0.09°W).

However, in this study, we analyzed only the theoretical potential, which is the highest level of resource potential and only takes into account restrictions concerning natural and climatic parameters. Thus, it is important to stress that the following different types of wind potentials should be considered for a deep wind resource assessment in forthcoming research:

Fig. 12. Spatial distribution of the 42 measurement points over Algeria, along with the outcomes from the WMW and KS tests between observations and ERA-Interim data for 2014 and at 10 m a.g.l. * indicates a rejection of the null hypothesis (no validation).

Fig. 13. Mean wind speed distribution over Algeria (contours), along with the prevailing wind direction (arrows), using ERA-Interim data for the period 1981–2014 at 10m a.g.l.

- Geographical potential is the theoretical potential limited by the resources at geographic locations that are suitable for installation of specific technologies, such as wind energy farms,
- Technical potential is the geographical potential that can be attained using technically available technologies while accounting for conversion efficiencies,
- Techno-economic potential is that achievable by applying technically feasible and economically-viable technologies universally used in competitive markets,
- Economic potential is the technical potential at cost levels considered competitive.

In several previous studies, these assessments were already

carried out for selected sites in Algeria [48–51].

4. Summary and conclusions

The present study contributes to a better assessment of the actual wind map in Algeria, using for the first time a reanalysis dataset. For this purpose, gridded 10 m zonal and meridional wind components from the ERA-Interim and for the period 1981–2014 were used. This dataset was also applied to assess the wind energy production potential over the whole of the Algerian territory.

The ERA-Interim data were validated with *in situ* measurements for 2014, collected by a network of 42 sites spread throughout Algeria. A good agreement between reanalysis and observations was found in the south, whereas a much weaker agreement was found near the coastline. At this point, it should be stressed that the ERA-Interim reanalysis is not able to capture local-scale wind features, particularly over the complex orography of mountainous areas. As such, in general, the agreement between reanalyzed wind and weather station wind measurements is not expected to be high, mostly over the aforementioned areas. To summarize:

- The MAE ranges from zero to 2.2 m s^{-1} by site, while it ranges from 0.47 m s^{-1} in the Sahara to 1.5 m s^{-1} in the coast by site classification;
- Concerning the MAPE by site, the minimum equals to zero at Batna in the Highlands, and a maximum of 107% at Ghazaouat near the Mediterranean coastline. By site classification, the MAPE varies between 12.71% in the Sahara sites and 61.18% in the Mediterranean coast;
- The KS and WMW test results reveal that among the 42 sites analyzed, 22 sites show an agreement between reanalysis and observations at least in one of the two tests.

Regarding the variability assessment of both the mean speed and prevailing winds, carried out at the monthly and hourly timescales, using the 33-year wind reanalysis dataset, it has been found that:

- The Algerian Sahara is windier than northern Algeria, where the maximum mean wind speed was assessed at In Salah (5.3 m s^{-1} with a predominantly east-northeasterly wind direction). The minimum mean wind speed equals to 2.3 m s^{-1} , predominantly northwesterly wind, was evaluated at Batna, northeastern Algeria.
- For southern Algeria, the windiest period is between March and August, while the period from October to December is much less windy.
- For the north, the windiest period is between February and April, while the less windy period is from June to October.
- During daytime (12 UTC), the Algerian territory is windy as a whole, while at nighttime winds are relatively calm.

The computed wind energy output for the Gamesa G52 (850 kW) provides reasonably high wind energy production potential $\approx 4 \text{ MWh day}^{-1}$ over most of the Algerian Sahara and of the Mediterranean coastline, where a maximum of 6 MWh day^{-1} can be achieved in the south.

Owing to the low density of weather stations over Algeria and to the lack of uninterrupted and homogeneous wind speed measurements, the use of reanalyses datasets can be a good alternative for wind resource assessments, providing some preliminary validation of the reanalyzed wind fields with observations. Nonetheless, ERA-Interim gridded wind fields were herein applied only for assessing large-scale wind features over Algeria. In sites where strong local winds play an important role, such as sea or mountain

Fig. 14. Monthly means of the 10 m wind speed distribution over Algeria (contours), along with the prevailing wind direction (arrows), using ERA-Interim data over the period 1981–2014.

Fig. 15. Hourly means of the 10 m wind speed distribution over Algeria, along with the prevailing wind direction, using ERA-Interim data for the period 1981–2014 at: (a) 00 UTC; (b) 06 UTC; (c) 12 UTC and (d) 18 UTC.

Fig. 16. The distribution of the daily wind energy potential (MWh day⁻¹) for the Gamesa G52 wind turbine, with a rated capacity of 850 kW at 55 m a.g.l.

breezes, catabatic and anabatic winds, the relatively coarse spatial resolution of the ERA-Interim reanalysis does not enable an accurate assessment of the actual wind power potential. For those cases, mesoscale and microscale models must be coupled with reanalysis so as to improve the spatial resolution of orography and to more realistically resolve the boundary layer and atmospheric turbulence effects on the wind fields. In forthcoming studies this should be foreseen for some target areas, where more accurate wind energy potential assessments are required, e.g. for planning the installation of wind farms.

Despite the limitations of the present study, it provides for the first time an assessment of the wind resource in Algeria over a relatively long time period (33 years) and on a regular grid covering the whole territory. Additionally, the mean wind and prevailing wind direction are also assessed on a sub-daily timescale, which is an innovative aspect of the present study. Since the present study confirms that most of the Algerian Sahara shows quite acceptable results for wind energy production, it is imperative to interconnect the electricity grid of the north with the south in the country to reach the 5 GW from wind source by 2030, already planned by the

governmental energy plan. Moreover, although the present study includes for the first time in Algeria the use of reanalysis data in the assessment of wind energy production potential, it is important to emphasize that future research will be conducted based on newly emerging products, such as the new ERA5 reanalysis dataset [52], which comprise important improvements in data quality and spatial resolution, thus allowing a verification and improvement of the present study results.

Hence, the outcomes of the present study not only contribute to a better characterization of the wind resource in Algeria, but may also assist in the selection of sites for the installation of new wind farms, envisioning an increase in the share of renewable energy to total energy production in Algeria.

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